International Journal of Modern Physics A,

QCD MEASUREMENTS IN PHOTON-PHOTON COLLISIONS AT LEP *

ÁKOS CSILLING†

Department of Physics and Astronomy, UCL,
Gower Street, London WC1E 6BT, United Kingdom

An overview of the latest results of the LEP collaborations on QCD measurements in photon-photon collisions is presented, including measurements of the total hadronic cross-section, the production of heavy quarks and dijets and the structure functions of real and virtual photons.

1. Introduction

Hadronic photon-photon interactions are responsible for the vast majority of hadron production in e^+e^- collisions at LEP2 energies. While soft processes have a large contribution to the total cross-section and non-perturbative phenomenological models are invoked to describe this data, various other QCD processes can also be measured in the perturbative region and compared to NLO predictions.

The high energy and large luminosity of LEP provides very high statistics samples of photon-photon interactions, allowing the improvement of earlier measurements both in terms of statistical power and in terms of the covered phase-space, as well as the measurement of hitherto unmeasured rare processes. The continuous improvement of the available Monte Carlo models and better data analysis techniques contribute to the reduction of systematic uncertainties.

An overview of the latest results of the LEP collaborations in the study of QCD processes in photon-photon interactions is presented.

2. Total Hadronic Cross-section

The total hadronic cross-section of quasi-real photon-photon collisions has been measured at LEP by L3[1] and OPAL[2] up to a photon-photon invariant mass of $W_{\gamma\gamma} = \sqrt{s_{\gamma\gamma}} = 145$ GeV, as shown in Figure 1. The visible invariant mass of each event is calculated from the particles observed in the detector, while the true $W_{\gamma\gamma}$ distribution has to be recovered by a statistical unfolding procedure which introduces correlations between data points. The photon flux is calculated by numerical integration over each bin, taking into account the finite virtuality of the incoming photons. Most of the systematic uncertainties involved in the measurement are due to our limited understanding of soft and diffractive processes, manifested in a large

*Talk presented at DPF 2000, Columbus, Ohio, August 2000.
†The author thanks the UK Particle Physics and Astronomy Research Council for their support.
Permanent address: KFKI Research Institute for Particle and Nuclear Physics, Budapest, P.O.Box 49, H-1525, Hungary; supported by the Hungarian Foundation for Scientific Research, OTKA F-023259.

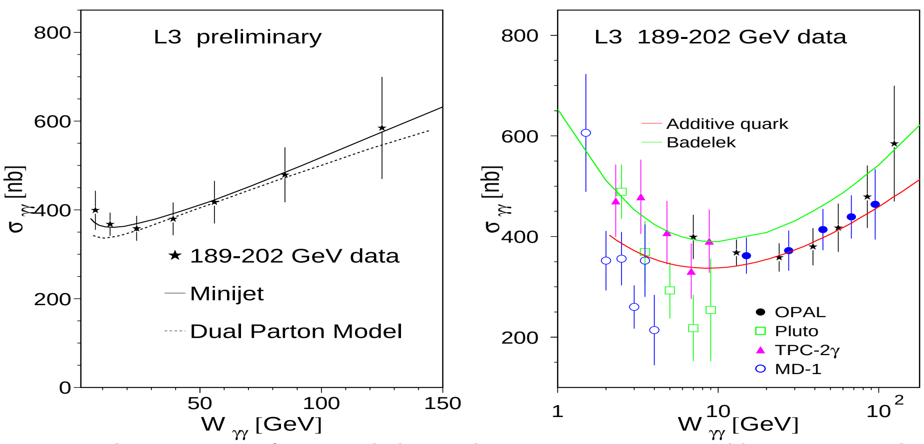

Fig. 1. Total cross-section of quasi-real photon-photon scattering measured by L3, compared with other experiments and various QCD models.

model-dependence of the unfolding procedure.

The total cross-section increases as a function of $W_{\gamma\gamma}$ faster than expected from the universal Donnachie-Landshoff fit. The observed energy dependence can be reproduced by introducing a hard Pomeron component to the fit, or by QCD models which attribute an important contribution to the hard scattering of the partons inside the photon.

3. Heavy Quark Production

The measurement of heavy quark production in photon-photon collisions provides a better test of QCD, because the large physical scale of the charm and beauty quark masses makes perturbative calculations more reliable.

Charm production has been measured[3,4,5,6] by the LEP collaborations using both the lepton-tag and the D*-tag methods. The first method uses the fact that most leptons observed in hadronic photon-photon collisions originate from semileptonic charm decay. The second method is based on the reconstruction of the $D^{*\pm} \to D^0\pi^\pm$ decay, which has a small combinatorial background due to the small difference of the $D^{*\pm}$ and D^0 masses. Both methods give consistent results, and all the recent measurements, shown in Figure 2 (left), lie within the wide band of theoretical uncertainties.

One should note that the large errors both on the experimental measurements and on the theoretical predictions can be reduced by restricting the considered phase space, since the largest uncertainty originates from the extrapolation to the kinematic region outside the detector acceptance. For example, the differential cross-section of D^* production measured as a function of its transverse momentum is shown in Figure 3 (left).

The differential cross-section of charm production as a function of $W_{\gamma\gamma}$ is shown in Figure 3 (right). A fast rise is observed towards high energies, much faster than

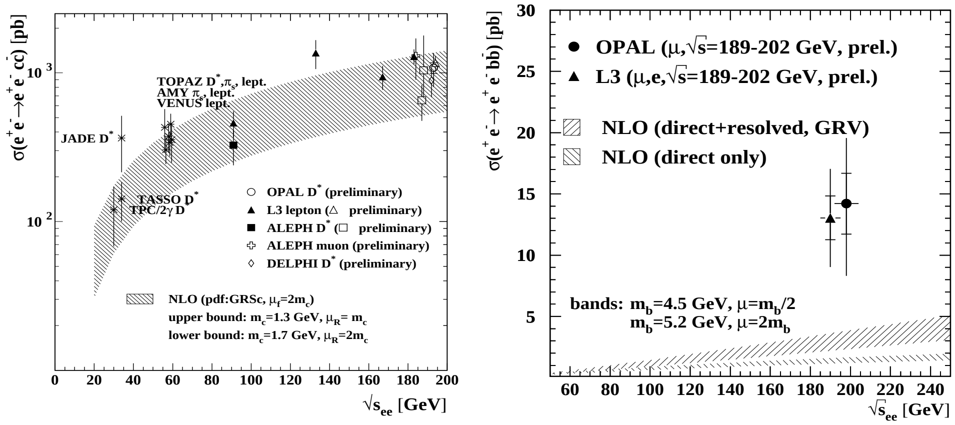

Fig. 2. Total cross-section of charm and beauty production in photon-photon collisions.

in the total cross-section, in agreement with measurements of the photoproduction of J/Ψ mesons at HERA.

Beauty production is expected to be suppressed by more than two orders of magnitude relative to charm production. It can be measured by exploiting the harder transverse momentum spectrum of muons produced from semileptonic b decays compared to other muon sources. The resulting cross-section of open beauty production[5,6] is significantly underestimated by the NLO prediction, while the L3 and OPAL measurements are in good agreement with each other, as shown in Figure 2 (right).

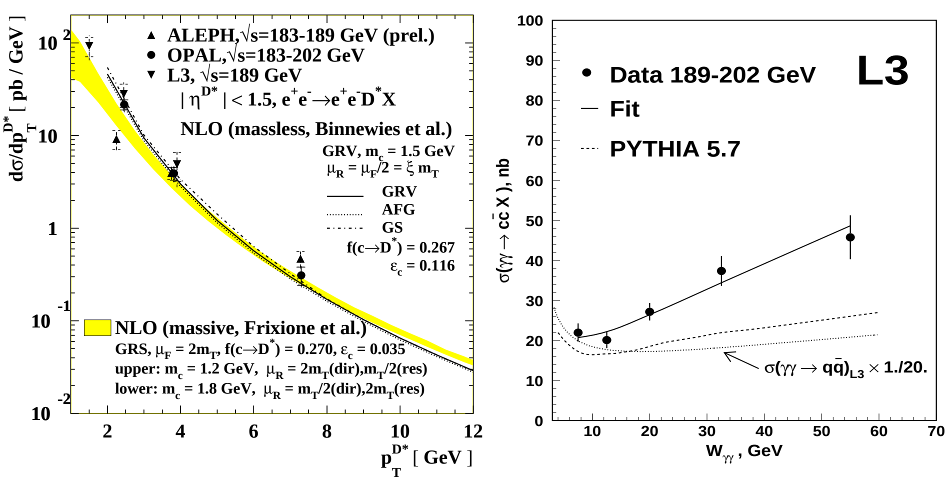

Fig. 3. Differential cross-section of D* production in photon-photon collisions, measured by ALEPH, L3 and OPAL, together with two different NLO calculations (left) and the differential cross-section of charm production as a function of $W_{\gamma\gamma}$ measured by L3 using the lepton-tag method.

4. Dijet Production

The production of jets in photon-photon collisions contains a hard scale, the transverse momentum, p_{T}, or transverse energy, E_{T}, of the jets, allowing the use of perturbative methods. Both ALEPH[7] and OPAL[8] find that the NLO calculations are able to describe the measured transverse energy and momentum distribution.

The quark and gluon contents of the photon can be separated by determining the fraction of the photon momenta carried by the jets, x_γ. Comparisons to the OPAL data[8] presented in Figure 4 (left) show that at low x_γ the gluon content of the photon is underestimated by the NLO calculation. The differences observed at large x_γ are due to hadronization effects not taken into account in the calculation.

Requiring a tagged photon in dijet events introduces another hard scale, the virtuality of the probe photon, Q^2, which is typically of a similar order of magnitude as p_{T}. Despite the theoretically more complicated nature of the problem, the ALEPH data[9] shown in Figure 4 (right) are well described by NLO calculations.

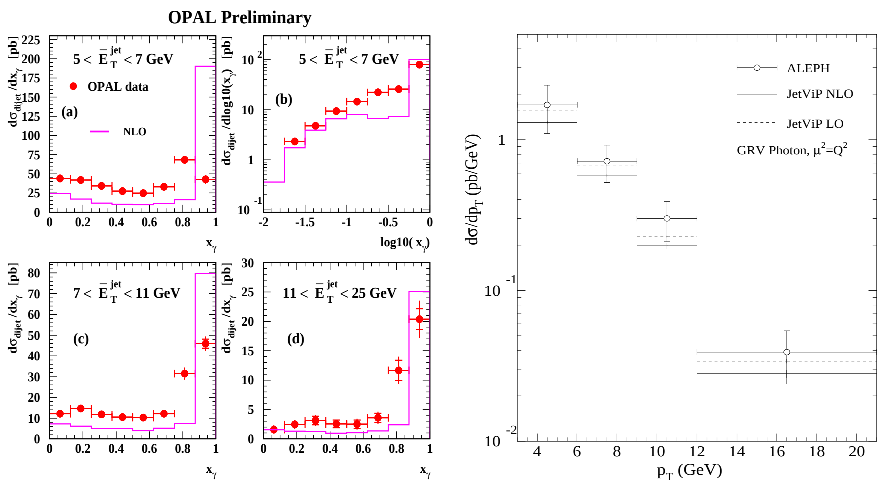

Fig. 4. Untagged dijet cross-sections as a function of x_γ from OPAL (left) and tagged dijet cross-section as a function of p_{T} from ALEPH (right) compared with NLO calculations.

5. Single and Double-tag Measurements

The structure of the photon can be measured in single-tag $\gamma^*\gamma$ collisions, regarded as deep inelastic electron-photon scattering. This classical measurement was extended at LEP to lower x and larger Q^2 values than ever before. Requiring a second tagging electron allows the study of the effective structure function of virtual photons if the virtualities are very different, or the investigation of the dynamics of highly virtual photon collisions if they are similar.

The recent measurement[10] of F_2^γ at low-x by OPAL has benefited from significant improvements of the available Monte Carlo models and also from the use of new methods, such as multi-variable unfolding, leading to smaller systematic uncertainties. While the data shown in Figure 5 (left) are completely consistent

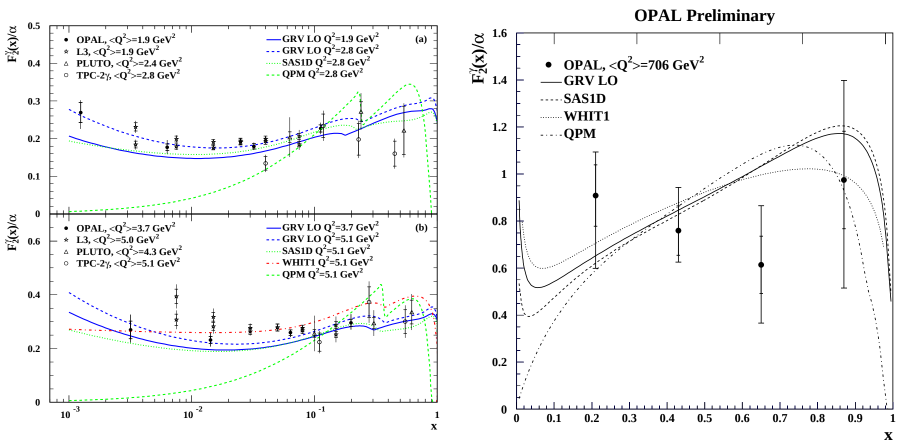

Fig. 5. The structure function of the photon at low x (left) and high Q^2 (right) measured by OPAL.

with the rise in F_2^γ towards lower values of x expected from QCD calculations, the obtained precision is still insufficient for a reliable confirmation. The high Q^2 measurement[11] of L3, using LEP1 data, reaches $Q^2 = 500$ GeV^2, while OPAL reaches $Q^2 = 2200$ GeV^2 in a preliminary analysis[12] of the LEP2 data, shown in Figure 5 (right).

The charm structure function of the photon has also been measured[13] by OPAL using the D*-tag method mentioned above to identify charm production in single-tag DIS events. This first measurement is well described by the theoretical expectations for $x > 0.1$, while at lower x values the predictions are below the data, with large statistical and extrapolation uncertainties.

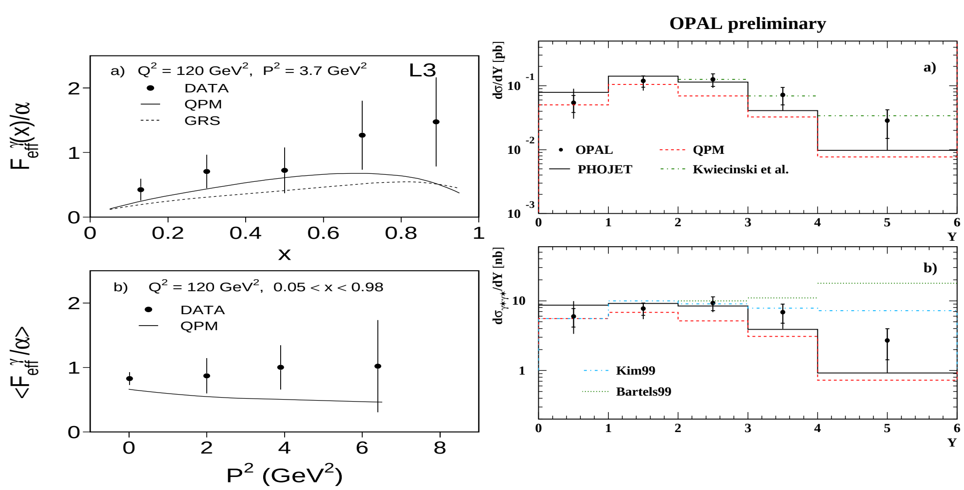

Fig. 6. The effective structure of the virtual photon measured by L3 (left) and the double-tag cross-section as a function of $Y \simeq \ln(W_{\gamma\gamma}^2/\sqrt{Q_1^2 Q_2^2})$ measured by OPAL (right).

L3 has measured the double-tag cross-section in terms of the effective structure function[11], shown in Figure 6 (left), and in terms of the double-tag cross-section of two highly virtual photons[14], similar to the OPAL measurement[15] presented in Figure 6 (right). In all these measurements the quark parton model calculation lies below the data, indicating contributions from additional processes, while the LO BFKL prediction overestimates the data, indicating important higher order corrections.

6. Conclusions

Several new and improved measurements of photon-initiated QCD processes at LEP have come out recently. In most cases we find a reasonable agreement with leading-order Monte Carlo models, and a good agreement with NLO QCD calculations. The vast amount of data collected by LEP promises more interesting results to come.

References

1. The L3 Collaboration, *Total Cross-Section in $\gamma\gamma$ Collisions at LEP*, L3 Note 2570.
2. The Opal Collaboration, G. Abbiendi et al., *Eur. Phys. J.* **C14** (2000) 199-212.
3. The ALEPH Collaboration, *Inclusive D^* Production in Two-Photon Events*, ALEPH 2000-070;
   The ALEPH Collaboration, *Study of Charm Production by Muon Tagging in Two Photon Interactions*, ALEPH 2000-031.
4. M. Chapkin, V. Obratztsov and A. Sokolov, *Inclusive D-meson and Λ_c Production in Two Photon Collisions at LEP*, DELPHI 2000-064.
5. The L3 Collaboration, *Cross-Section Measurement of Charm Production in $\gamma\gamma$ Collisions at LEP*, L3 Note 2548;
   The L3 Collaboration, *Beauty Production in $\gamma\gamma$ Collisions at LEP*, L3 Note 2565;
   The L3 Collaboration, M. Acciarri et al., *Phys. Lett.* **B 467** (1999) 137-146.
6. The OPAL Collaboration, *Inclusive Production of $D^{*\pm}$ Mesons in Photon-Photon Collisions at $\sqrt{s_{\rm ee}} = 183 - 202$ GeV*, OPAL PN 453;
   The OPAL Collaboration, *Measurement of Open Beauty Production in Photon-Photon Collisions at $\sqrt{s_{\rm ee}} = 183 - 202$ GeV*, OPAL PN 455.
7. The ALEPH Collaboration, *A Measurement of the Di-Jet Cross-Section in $\gamma\gamma \rightarrow$ hadrons*, ALEPH 2000-052.
8. The OPAL Collaboration, *Di-jet Production in Photon-Photon Collisions at $\sqrt{s_{\rm ee}}$ from 189 to 202 GeV*, OPAL PN 443.
9. The ALEPH Collaboration, *A Measurement of the Di-Jet Cross-Section in Single-Tagged $\gamma\gamma \rightarrow$ hadrons*, ALEPH 2000-066.
10. The OPAL Collaboration, G. Abbiendi et al., CERN-EP-2000-082, hep-ex/0007018, submitted to *Eur. Phys. J.* **C**
11. The L3 Collaboration, M. Acciarri et al., *Phys. Lett.* **B 479** (2000) 373-386.
12. The OPAL Collaboration, *A High-Q^2 Measurement of the Photon Structure Function F_2^γ at LEP2*, OPAL PN 454.
13. The OPAL Collaboration, G. Abbiendi et al., *Eur. Phys. J.* **C 16** (2000) 579-596.
14. The L3 Collaboration, *Double Tag Events in Two-Photon Collisions at LEP*, L3 Note 2568.
15. The OPAL Collaboration, *Measurement of Double-Tagged Events in Two-Photon Collisions at LEP*, OPAL PN 456.